Solid State Transformer Control Aspects For Various Smart Grid Scenarios

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Abstract—The power distribution networks can be classified as active/passive and stiff/weak based on the nature of loads and network impedances. As an alternative to the conventional iron-and-copper based passive transformer, a solid state transformer (SST) can be used for interfacing such distribution networks to the medium voltage AC grids. Although the power architectures of SST for distribution grids are studied in detail, the control schemes for SST considering the nature of network is yet to be explored. In this paper, the control aspects for the popular three-stage cascaded multilevel solid state transformer (CMSST) are studied for the following grid scenarios: (i) SST interfacing two stiff grids, (ii) SST interfacing a stiff grid and a weak grid, and (iii) SST interfacing a stiff grid with a passive network. In this context, an average model of the CMSST is developed by replacing the basic switching cell (H-bridge) with its equivalent average model. It is shown that the control aspects are network specific and are not interchangeable.

1. INTRODUCTION

Integration of distributed energy resources (DER) and electric vehicles (EV) into the distribution networks has opened up many problems such as voltage instability, protection malfunction and unintentional islanding etc., [1]-[3]. Until now the distribution networks are connected to the medium voltage (MV) grids through an iron-and-copper based passive transformer at the distribution substation. Due to the passive nature of the conventional transformer, any disturbances on the distribution networks will be reflected onto the MV grid and eventually healthy networks will be affected. A solid state transformer (SST) can solve these problems in the distribution network by not only facilitating a controlled bidirectional flow of active and reactive powers, but also providing a stiff DC bus for decoupling the disturbance on both sides of the transformer. The distributed energy storage (DES) devices, EV loads and DERs can be integrated into the DC bus of the SST. However, realizing an SST that can compete with the conventional transformer internms of efficiency and reliability itself is a challenge [4], [5].

Various SST architectures viz., fully-modular, semi-modular and non-modular architectures are being explored keeping in mind the functionalities that it has to provide for distribution grids [6], [7]. A three-stage cascaded multilevel SST (CMSST) is a popular fully-modular SST architecture that is studied more often for distribution grid applications [8]-[10]. The three-stage CMSST architecture, which is hereafter referred to as an SST, has three stages. Stage-1 consists of a cascaded multilevel AC-DC rectifier to convert medium voltage AC (MVAC) to medium voltage DC (MVDC). A high frequency transformer isolated dual active bridge (DAB) is used in stage-2 to convert MVDC to low voltage DC (LVDC). Finally, a three-phase inverter in stage-3 converts LVDC to low voltage AC (LVAC). The reliability of this fully-modular SST architecture can be improved by integrating extra healthy redundant modules and put them to operation in the event of any fault in the active modules [11].

The power conversion stages of the three-stage CMSST have been standardized by comparing various options, for example, resonant DC-DC converters are compared with non-resonant type DC-DC converters to find a suitable choice for isolation stage [12]. Similarly, various multilevel architectures viz., cascaded H-bridge, cascaded neutral point clamped (NPC) and flying capacitor (FC) multilevel configurations are compared and the cascaded H-bridge is preferred in the first stage of the CMSST especially for higher number of levels [13], [14]. However, the control aspects of the three-stage CMSST have not been explored in depth. In most of the SST experiments, the LVAC side is considered as a passive network and the SST is designed to act as a grid forming converter [15], [16]. In [17], the LVAC grid is modelled as a voltage source neglecting the impedance of the distribution network which is not practical because most of the distribution networks are either resistive or inductive depending on the length of feeder. Hence, the focus of this paper is to explore various grid scenarios, understand them and propose suitable control techniques for the SST.

Power networks/grids can be classified as active and passive depending on the nature of loads connected to the network. Now-a-days, most of the distribution networks are becoming active due to the integration of DES and DER. Some of the unforeseen challenges with the active distribution networks are the reverse power flow at the distribution transformer, voltage raise, voltage flicker, harmonics, unexpected islanding and sympathetic tripping [2]. Although researchers have coined several solutions for these problems such as dynamic on-load tap changers and reactive control of DER etc., the solution are limited by the nature of the network [18]. The second classification of power grids is based on the impedance, whether it is a strong grid or a weak network.

A detailed analysis on the classification of AC networks and loads is presented in Section II of this paper. Rest of the paper is organized as follows. The three-stage CMSST and
its average model are introduced in Section III. A detailed analysis on the control aspects for the SST considering the following scenarios: (i) SST interfacing two stiff grids, (ii) SST interfacing a stiff grid with a weak grid, (iii) SST interfacing a stiff grid with a passive network are discussed in Section IV. PLECS simulation results are presented for each case to validate the analysis. Section V concludes the paper.

II. CLASSIFICATION AND CHARACTERISTICS OF GRIDS

Considering the quality and variations in the voltage and frequency at the point of common coupling (PCC), AC grids can be classified into three categories: (i) stiff/strong grids, (ii) weak grids and (iii) passive grid/network. In this section, the dependency of voltage and frequency at the PCC on the load are studied for various grids.

A. Stiff grid

In a stiff grid, the voltage and frequency at the PCC will remain constant irrespective of the direction and magnitude of active and reactive powers. The stiff grids can be modelled using a voltage source and a small series impedance as shown in Fig. 1. Where, CPL stands for constant power loads. A generator feeding a small distance transmission feeder is a good example of stiff grid.

*Characteristics of the stiff grid:*

1) Voltage and frequency at the PCC is decided by the grid voltage \(V_g\) and grid frequency \(f_g\) irrespective of the load.
2) CPL will not affect the voltage at the PCC because of low grid impedance \(Z_s \approx 0\).
3) Power flow at the PCC can be bidirectional as it does not affect the voltage or frequency at the PCC. The bidirectional flow of active and reactive powers does not have any limitations in this case.

B. Weak grid

A grid is said to be weak when the voltage and frequency at the PCC changes with respect to the magnitude and direction of active and reactive power drawn by the load. The weak grid can be modelled as a source in series with a large impedance as shown in Fig. 2. Examples of weak grids are a radial distribution network, islanded micro grids, etc.

*Characteristics of the weak grid:*

1) Voltage at the PCC is decided by the active and reactive power drawn by the load.
2) CPLs will affect the voltage at the PCC because of high grid impedance.
3) The reverse flow of both active and reactive power at the PCC should be limited as it can make the PCC voltage to hit the upper or lower limits, triggering the protection equipment.

C. Passive network

A network is said to be passive when it does not have any active elements like DERs as shown in Fig. 3. Any distribution network without distributed generation and energy storage is a good example of the passive network. The arguments made earlier for stiff and weak grids are valid in this case as well expect that the reverse power flow at the PCC is not possible.

When a solid state transformer (SST) is interfaced into the grid, the control aspects of the SST depend on the grid requirements at PCC i.e., voltage and frequency regulation, active and reactive power flow control etc. Since the grid requirements at the PCC depend on the nature of the grid, it is necessary to choose appropriate control architectures for the SST for different grid cases. The details are presented in the subsequent sections.

III. SOLID STATE TRANSFORMER ARCHITECTURE

A solid state transformer is used to interface two networks/grids as shown in Fig. 4. An SST can be viewed as a three terminal transformer with two AC ports connected to MVAC and LVAC grids and a DC port that can be used to interface DES and DER. In a conventional transformer, the active and reactive power flow from primary side to secondary side is unregulated, the secondary side voltage and frequency are dictated by the primary side voltage and frequency respectively, and any disturbance on either sides will be reflected on the other side. However, an SST provides feasibility to control the bidirectional flow of both active
and reactive power, regulate the voltage and frequency of secondary side independent of the primary side voltage and frequency, and disturbance decoupling is possible due to the intermediate DC port. Due to such attractive features, SST will become a suitable alternative for the conventional transformer. As shown in Fig. 4, a three-stage CMSST architecture which has been widely discussed in literature is considered in this study. The operation and basic control schemes of the three-stage CMSST are discussed in [8]–[10] and are not discussed here again.

A. SST modelling

To validate the control aspects of the SST, the average model of an SST is developed first. Details of the average models are presented in this section. The basic switching cell of the three-stage CMSST presented in Fig. 4 is a H-bridge. The pole voltage \( v_p \) and DC bus current \( i_{dc} \) of the basic switching cell are functions of modulation indices (\( m_a1 \) and \( m_a2 \)), input current \( i_{g} \) and DC bus voltage \( v_{dc} \). The pole voltage \( v_p \) and DC bus current \( i_{dc} \) can be modelled as controlled voltage and controlled current sources as shown in Fig. 5. Therefore, the complete average model of the SST can be developed by replacing the basic H-bridge switching cell with its average model. Where, \( m_a1 \) and \( m_a2 \) are the modulation indices of two legs of the H-bridge and are given as follows:

\[
m_{a1} = \frac{1 + m_{a2}}{2} \quad \text{and} \quad m_{a2} = \frac{1 - m_{a1}}{2};
\]

where, \( m_a \) is the modulation index from the controller. The developed average model of the SST retains all the dynamics due to the filter elements (inductors and capacitors) and controllers. Hence, this is a most suitable model that is useful while working on the system level simulations. The control aspects of the SST are discussed in the subsequent section.

### IV. Control Aspects of the SST

As stated earlier, the control aspects of the SST depend on the type of grid to which it is interfaced, i.e., whether it is interfaced to a stiff grid or a weak grid or a passive network. The control aspects of SST for the following cases are discussed in detail in the rest of the paper.

1) SST interfacing two stiff grids.
2) SST interfacing a stiff grid with a weak grid.
3) SST interfacing a stiff grid with a passive network.

#### A. SST interfacing two stiff grids

An SST interfacing two stiff grids is shown in Fig. 6. As stated before, the voltage at the PCC of the MVAC side is dictated by the source voltage \( v_1 \). Similarly, the voltage at the PCC of the LVAC side is decided by the LVAC grid voltage \( v_2 \). This is mainly because of negligible source impedance (i.e., \( Z_s \approx 0 \)) in stiff grids. The SST control objectives and requirements in this case are as follows:

1) To regulate the active power flow between MVAC and LVAC grids. This can be achieved by incorporating a power flow controller in the isolation stage. Since the MVAC and LVAC grid are stiff in nature, it is not necessary to limit the negative power from one grid to another.

<table>
<thead>
<tr>
<th>Table I: Simulation parameters</th>
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<tr>
<td>Parameter name</td>
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<tr>
<td>MVAC side specifications</td>
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<tr>
<td>Grid phase voltage</td>
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<td>Grid frequency</td>
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<td>LVAC side specifications</td>
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<td>MVDC load specifications</td>
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<td>Active power (linear load)</td>
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<td>Reactive power (linear load)</td>
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<tr>
<td>Active power (non-linear load)</td>
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<tr>
<td>Specifications of the SST</td>
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<tr>
<td>Number of series H-bridge in stage 1</td>
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<tr>
<td>MVAC side filter inductor</td>
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<tr>
<td>MVDC bus capacitors</td>
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<tr>
<td>LVDC bus capacitors</td>
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<td>LVAC side filter inductor</td>
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Figure 4: A three-stage CMSST with its block representation.

Figure 5: Average model for the basic H-bridge cell in an SST.

Table I: Simulation parameters
2) To support the MVAC and LVAC grids with required reactive power. This can be achieved by incorporating the d-q control or P-Q control in the multilevel rectifier stage and inverter stage.

3) Any disturbances such as harmonic currents, voltage sag and swell as a result of faults etc., on the MVAC side should not be reflected on to the LVAC side and vice versa. This can be achieved by choosing sufficient energy buffer at the DC bus.

Based on the above mentioned objectives, the control architecture for the SST can be as shown in the Fig. 7. The DC bus controllers in the first and third stages regulate the MVDC and LVDC bus voltages respectively. According to the current reference given to the DAB in the second stage, power will be transferred between the two regulated DC buses. Using the average model, the SST interfacing two stiff grids case is simulated in PLECS simulation software for the specifications shown in Table. I. The active and reactive power references provided to the SST are shown in Table. II.

The simulation results showing the active and reactive power delivered by the LVAC grid and SST, and DC bus voltages of SST for various cases are presented in Fig. 8 and 9. It is evident from these results that the SST can control the active and reactive power transferred to the LVAC grid. It can be observed from Fig. 9 that the maximum peak overshoot of the LVDC voltage is about 50 V, where as the maximum peak overshoot in the MVDC bus is less than 10 V. It can be concluded from these results that it is possible to mitigate the effect of LVAC side disturbances on the MVAC side.
B. SST interfacing stiff grid with a passive network

An SST interfacing a stiff grid with a passive network is shown in Fig. 10. The voltage and frequency at the PCC of the MVAC side are dictated by the source voltage $v_1$ and source frequency $f_1$ as the MVAC grid is stiff in nature. The voltage and frequency at the PCC of the LVAC side has to be provided by the SST as the LVAC network is passive in nature. The control objectives and requirements in this case are as follows:

1) To provide the LVAC grid with a stable voltage source, whose voltage and frequency have to be maintained constant within certain tolerance irrespective of the load variations. This can be achieved by controlling the inverter stage as a grid forming inverter.
2) To support the MVAC grid with required reactive power which can be achieved by using a P-Q or a d-q control as explained earlier.
3) Any disturbances such as harmonic currents, voltage sag and swell as a result of sudden variations in load on LVAC side should not be reflected on to the MVAC side. Sufficient energy buffer at LVDC and MVDC buses will help in this case.

As shown in Fig. 11, a control scheme for the SST is designed to fulfill the above mentioned objectives. Unlike the control in two stiff grids case, the LVDC bus should be regulated at a fixed value by the DAB. In the proposed control, a simple voltage controller is used to perform this task. Alternatively a cascaded two loop control can be used to achieve better dynamic performance. It should be noted that while designing the grid forming inverter, the output impedance of the SST (LVAC side) should be designed appropriately. High output impedance can cause distortion in the terminal voltage when harmonic loads are present in the passive network. It can be seen from the simulation results presented in Fig. 12 that the SST can support a passive network by behaving as a grid forming converter.

C. SST interfacing stiff grid with a weak grid

As mentioned in Section II, fluctuation or flickering of voltages at the PCC is a major concern in weak distribution network. One of the reasons for this voltage instability is the intermittent distributed power generation (DG) especially when the load in the distribution network is less than the generated power from the DG. Several power management

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<th>Time stamp</th>
<th>$P_{ref}$ (kW)</th>
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<td>$t = 0$ Sec</td>
<td>0</td>
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<tr>
<td>$t = 5$ Sec</td>
<td>-20</td>
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<td>$t = 10$ Sec</td>
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<tr>
<td>$t = 15$ Sec</td>
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methods were proposed in literature, for example [19], to manage the power in an islanded microgrid. Such methods can be extended to the weak network case when it is interfaced to the grid through an SST and voltage at the PCC can be regulated by controlling the reverse power flow from LV side to MV side. Recent work published in [20] is along the similar lines.

V. CONCLUSION

The control aspects of a three-stage cascaded multilevel SST for various grid scenarios are studied in detail in this paper. The scenarios considered during this study include (i) SST interfacing two stiff grids, (ii) SST interfacing a stiff grid and a weak grid and (iii) SST interfacing a stiff grid and a passive network. Followings are the summary of the control objectives for the above mentioned scenarios:

1) The control objectives are straightforward when SST is interfaced between two stiff grids, i.e., (a) A d-q control in the first stage regulates the MVAC bus and controls the reactive power flow to the MVAC grid; (b) A d-q/p-q control in the third stage regulates the LVAC bus voltage and controls the reactive power flow to the LVAC grid; and (c) A current controller in the DAB stage can control the power flow between MVDC and LVDC bus.

2) When an SST interfaces a stiff grid to a passive network, the control objectives differ in the second and third stages. The isolation stage has to be controlled to regulate the LVDC bus at a fixed reference. The control in the third stage will be to regulate the LVAC voltage as it needs to behave like a grid forming inverter.

3) The control becomes complicated when the SST is interfaced between a stiff grid and a weak grid. Popular control schemes such as “droop controllers” or “virtual synchronous generator” can be implemented in the inverter stage to improve the voltage stability of the LVAC grid.

The average model of the SST is simulated in PLECS simulation platform to verify the designed control schemes. The presented simulation results confirm that the designed control schemes meet the control objectives considered for various cases.

REFERENCES